Dissipating the Steam:
How Spatial Spillovers influenced the Diffusion of Steam Engines during the British Industrial Revolution

Sara Savini

Università degli Studi dell'Insubria, Varese (Italy)

Bordeaux School of Economics, CNRS, INRAE, UMR 6060, UMR 1441, F-33600 Pessac, France

I – BACKGROUND

Historians have long taken an interest in analysing the diffusion of steam engines and its relation to the Industrial Revolution. While very different aspects have been studied through the years, the interrelationships between territories, the role of distance, and their impact on the dissemination of this innovation remain comparatively understudied[1].

The aim of this paper is to analyse whether imitative behaviour, proximity to adoption leaders and neighbours' characteristics played a role in the diffusion of early steam engines across counties during the first phase of the British Industrial Revolution, up to 1800. To this end, I use spatial econometric techniques and models to identify and quantify the spatial autocorrelation and spillovers that influenced the adoption patterns of steam engines across English counties.

While there is a substantial body of literature examining the regional variation in the diffusion of this innovation, there has been a relative lack of connection to research on innovation diffusion in other fields, such as economics. This has contributed to the underdevelopment of a narrative that explores the interrelationship between territories. Indeed, steam engine diffusion studies in the USA examine the economic viability of this innovation in comparison to water power[2] and the shift from manual to steam-powered work[3]. In Germany, recent studies have explored the relationship between the location of steam-powered industries and the territorial presence of coal[4]. Studies on the French case concern various debates, among which the relations between industrialisation and human capital accumulation stands out[5]. However, very recent contributions have initiated a debate on the role of distance to

---

[1] Gutberlet, '*Mechanization and the Spatial Distribution of Industries in the German Empire, 1875 to 1907*'; Chapelain and Wilke, '*Steam Technology Diffusion in the 19th Century - First Evidence from Spatial Panel Data*'.
[2] Atack, Bateman, and Weiss, '*The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing*'.
[3] Atack, Margo, and Rhode, '"*Mechanization Takes Command*"'.
[4] Gutberlet, '*Mechanization and the Spatial Distribution of Industries in the German Empire, 1875 to 1907*'.
[5] Diebolt, Chapelain, and Menard, '*Industrialization as a Deskilling Process? Steam Engines and Human Capital in XIXth Century France*'; Diebolt, Le Chapelain, and Menard, '*Learning Outside the Factory*'.

adoption leaders for the diffusion of steam engines across French department[6]. In the case of UK, the pioneering works of Von Tunzelmann[7] and Kanefsky and Robey[8] established the groundwork for studies on geographical variation in adoption across regions. These were traced back to heterogeneity in a set of dimensions, including factor prices and the industrial base of the county[9].

More in general, a narrative of the "*spottiness*" of the Industrial Revolution and how it contributed to reinforce linkages among territories with high-level of spatial diversity has gained consensus in the literature with the pioneering works of historians such as Pollard[10] and Hudson[11]. This promoted historical research more attentive to territorial heterogeneity and the relations among regions and sub-regions. At the same time, spatial autocorrelation and spatial spillovers are considered important dimensions in innovation diffusion's literature, and technology diffusion has been shown to be both spatially heterogeneous and observational units spatially dependent[12]. In particular, geography influences innovation diffusion in two ways: there is an inverse relationship between geographical distance and diffusion of ideas, knowledge, and innovation[13]; and neighbours' characteristics tend to spill over and influence innovation adoption[14] (*neighbourhood effect*). However, no analysis to date explicitly identifies and quantifies these phenomena and their influence on the diffusion of early steam engines. This paper is positioned at the centre of this debate.

II – CLUSTERS AND SPATIAL AGGLOMERATION OF STEAM ENGINES

For the following analyses, I use the 2020-updated *Database of Early Steam Engines* from Kanefsky and Robey. The database records numerous information for each engine recorded, but I focus on the year associated to the construction and the relative county (for a subset of engines, also the exact location is available and used for point pattern analysis)[15].

Analysis of global measures of spatial autocorrelation shows the existence of significant, positive spatial autocorrelation in the adoption of steam engines during the early stages of the British Industrial

---

[6] Chapelain and Wilke, '*Steam Technology Diffusion in the 19th Century - First Evidence from Spatial Panel Data*'.
[7] Von Tunzelmann, *Steam Power and British Industrialization to 1860*.
[8] Kanefsky and Robey, '*Steam Engines in 18th-Century Britain*'.
[9] Nuvolari, Verspagen, and Von Tunzelmann, '*The Early Diffusion of the Steam Engine in Britain, 1700–1800*'.
[10] Pollard, '*Industrialization and the European Economy*'; Pollard, *Peaceful Conquest*.
[11] Hudson, '*Regions and Industries: A Perspective on the Industrial Revolution in Britain*'; Hudson, *The Industrial Revolution*.
[12] Cox and Figueroa, '*Agglomeration and Creativity in Early Modern Britain*'; von Graevenitz, Graham, and Myers, '*Distance (Still) Hampers Diffusion of Innovations*'.
[13] Tobler, '*A Computer Movie Simulating Urban Growth in the Detroit Region*'; Comin, Dmitriev, and Rossi-Hansberg, '*The Spatial Diffusion of Technology*'.
[14] Brown and Cox, '*Empirical Regularities in the Diffusion of Innovations*'; Koo, '*Determinants of Localized Technology Spillovers*'; Kaur, Punia Nakai, and Kaur, '*Spatial Spillover of Product Innovation in the Manufacturing Sector*'.
[15] For a throughout discussion of the source I suggest the reading of the original publication by Kanefsky and Robey, *'Steam Engines in 18th-Century Britain: A Quantitative Assessment'*, as well as '*The early diffusion of the steam engine in Britain, 1700–1800: a reappraisal'* by Nuvolari, Verspagen, and Von Tunzelmann, who point out some possible biases of the source. Given the continuous updating work and its coverage, this database remains the best source available.

Revolution. This indicates that, in contrast to a random distribution of adoptions across English counties, the adoption of steam engines was influenced by the level of adoption in neighbouring counties. This is coherent with the large body of literature on the importance of neighbours' characteristics in influencing the adoption behaviour of the focal region.

Table 1: Global measures of spatial autocorrelation (engines built in the period 1770-1800) according to proximity based weighting matrix W and inverse-distance with 120 km cut-off M weighting matrix.
source: own elaborations on Early Engines' database (Kanefsky and Robey, updated 2020)

Global Indicator	Statistics	p-value
Moran's I		
W	0.2676	1.743e-05
M	0.2210	4.023e-07
Geary's C		
W	0.7505	0.0143
M	0.6399	8.022e-06

In order to push further and uncover these complex dynamics, I then analyse local indicators of spatial autocorrelation[16] (LISA) to complement the global analysis.

The resulting maps in Figure 1 clearly highlight the presence of *hot spots* on the English territory[17], and are coherent with historical analyses of the territories. For instance, the central part of England, on the area comprising the counties of Cumberland, Westmorland, Durham, Lancashire, Yorkshire, Cheshire, Derbyshire, and Nottinghamshire form a cluster of positive, significant spatial autocorrelation, according to the local Moran's I statistics (map on the left side). This means that counties included in the cluster would display similarly high level of steam engines adoption. Given that these counties encompass a significant portion of the coal-rich Midlands, this result is not unexpected. A supplementary analysis can be conducted by examining the map of the local Geary's C statistics, which identifies a similar set of counties but is more responsive to local behavioural patterns, thereby presenting a somewhat distinct representation. It is notable that Westmorland and Durham, Cheshire, Derbyshire, Nottinghamshire, and Lincolnshire are still regarded as part of the broader Lancashire and Yorkshire cluster. However, they exhibit comparatively lower rates of adoption of steam engines in contrast to the more industrialised counties within the same cluster. This

[16] I employ the Local Moran's I, the Local Geary's C and the Local Getis-Ord's G estimated with 99,999 permutations (the maximum allowed by the software) in order to display very strict levels of significance (α = 0.05 being the laxest level of significance considered). I consider the topology of the territories as represented by a proximity matrix W for which neighbours are defined as those areas sharing at least a border.
[17] Some differences in the clusters identified are normal, across the indicators considered, as they are more or less sensitive to the presence of local variations.

is coherent with Beckett and Heath's analysis of *East* Midlands, their technological backwardness up to the 1840s, and their marked difference from the industrial experience of Lancashire[18].

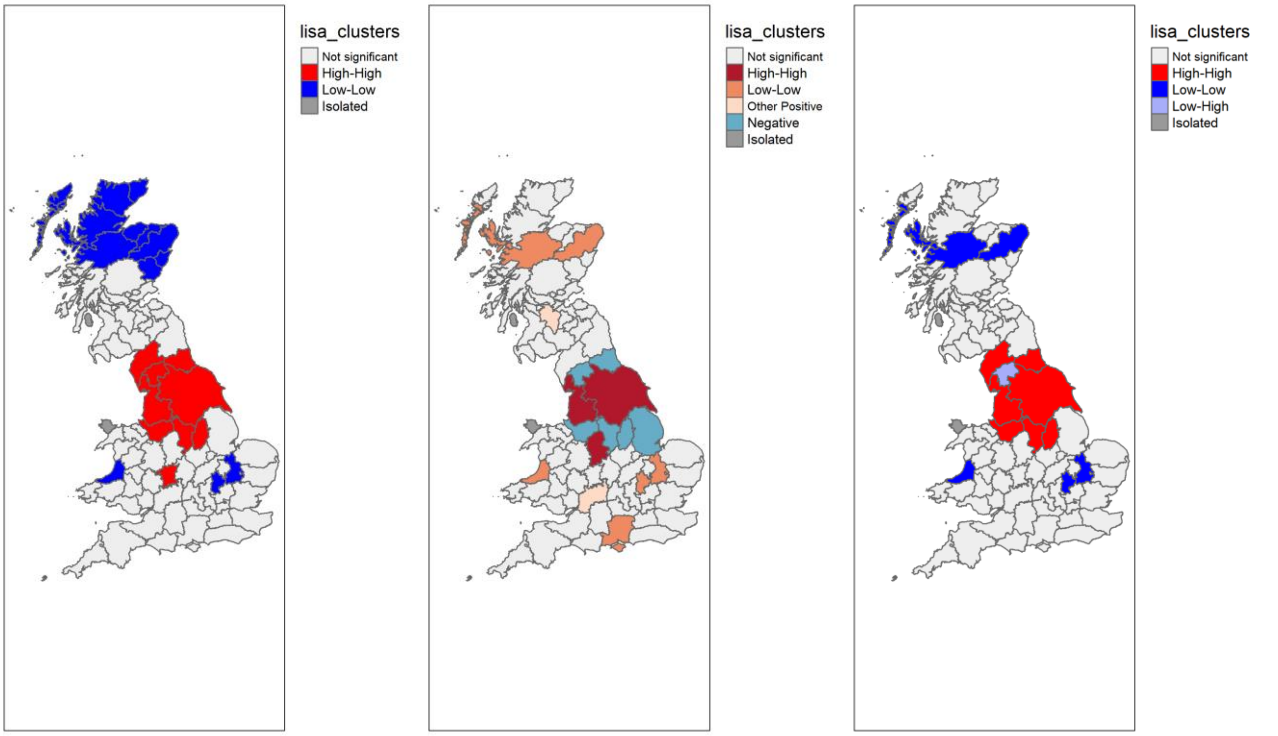

Figure 1: on the left, local Moran's I, in the centre, local Geary's C, on the right, local Getis-Ord's G for historical counties of UK (engines built in the period 1770-1800)
source: own elaborations on Early Engines' database (Kanefsky and Robey, updated 2020)

In order to gain a more precise understanding of the interactions involved in the adoption of early steam engines, a finer-grained analysis of a subset of the available data is possible, with point pattern analysis. I show the exact location of 1,752 engines in Figure 2.

[18] Beckett and Heath, '*When Was The Industrial Revolution In The East Midlands?*'

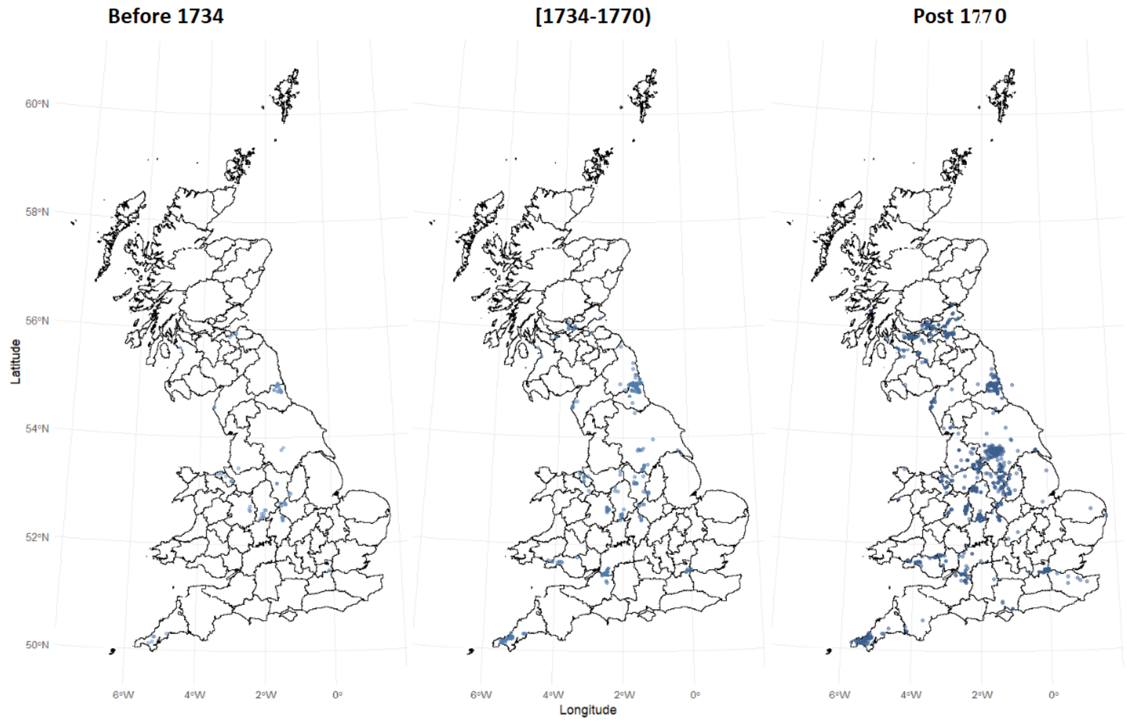

Figure 2: map of locations of steam engines adoption per time period.
source: own elaborations on Early Engines' database (Kanefsky and Robey, updated 2020)

The analysis of the clustering tendencies of the points representing steam engines through the Nearest Neighbour Distance function G[19] highlights a systematic pattern of clustering of the points through every decade of the dataset. Indeed, the observed pattern of nearest-neighbour distance suggests close-range clustering, i.e. significantly shorter distance between the points than expected under complete spatial randomness. The analysis of the Ripley's K function at multiple spatial scales[20] also corroborates the presence of clustering at shorter distances, while the results indicate a tendency towards slight reduced clustering at greater distances. This confirms a distance decay in the technology adoption behaviour and highlights how neighbouring observations tend to present similar adoption behaviour. The analysis of the points of adoption provides a coherent reiteration of the importance of spatial autocorrelation and distance considerations in the adoption patterns of steam engines.

---

[19] In spatial point pattern analysis, the nearest neighbour G function, G(r), represents the cumulative distribution function of the distances from a typical point in the pattern to its nearest neighbouring point. Specifically, G(r) denotes the probability that the nearest neighbour distance is less than or equal to r.

[20] Ripley's K function, K(r), is a second-order statistic used in spatial point pattern analysis to evaluate the spatial dependence of points over various scales. It is defined such that $\lambda K(r)$ equals the expected number of additional points within a distance r of a typical point, where λ is the intensity (mean number of points per unit area) of the process.

III – SPATIAL ECONOMETRIC MODELS FOR STEAM ENGINES' DIFFUSION

The second quantitative exercise is the estimation of spatial econometric models, which explicitly quantify spatial spillovers arising from imitative behaviour and other agglomerative phenomena.

Due to a lack of data in the explanatory variables, I restrict this part of the analysis to the pooled period of engines installed in 1770-1800 per county, thus obtaining cross-sectional models. The dependent variable is $\log(SteamEngine + 1)$. The other dimensions included in the analysis, all at county-level, follow Nuvolari, Verspagen, and Von Tunzelmann[21]:

- The number of cotton and wool mills c.1800[22]
- The number of blast furnaces in operation c.1800[23]
- The number of mines c.1800[24]
- The output of coal mines, in thousands of tons, in 1800[25]
- The number of waterwheels c.1800[26]
- The (log-transformed) population size in 1801[27]

I add the topology of the regions involved by constructing a *W* matrix based on county contiguity and another one, M, based on inverse distance with a threshold cut-off of 120 kilometres. Let *X* the matrix of all independent variables.

1: Spatial AutoRegressive model (SAR)

$$\log(SteamEngine_i + 1) = \rho * W_i * [\log(SteamEngine_i + 1)] + \beta_i * X_i + \epsilon_i$$

2: Spatial Durbin Model (SDM)

$$\log(SteamEngine_i + 1) = \rho * W_i * [\log(SteamEngine_i + 1)] + \beta_i * X_i + W_i\,\theta_i X_i + \epsilon_i$$

3: Spatial Lag of X model (SLX)

$$\log(SteamEngine_i + 1) = \beta_i * X_i + W_i\,\theta_i X_i + \epsilon_i$$

The most general model estimated (Equation 2) is a Spatial Durbin Model, with spillovers both in steam engines' variable (indicating imitative behaviours) and in the explanatory variables (indicating other agglomerative behaviours). Variants, such as the SAR (Equation 1) and SLX (Equation 3)

[21] Nuvolari, Verspagen, and Von Tunzelmann, '*The Early Diffusion of the Steam Engine in Britain, 1700–1800*'.
[22] Chapman, '*Fixed Capital Formation in the British Cotton Industry, 1770–1815*'.
[23] Scrivenor, *History of the Iron Trade*.
[24] Nuvolari, Verspagen, and von Tunzelmann, '*The Early Diffusion of the Steam Engine in Britain, 1700–1800*'.
[25] Flinn, *The History of the British Coal Industry*.
[26] Kanefsky, *The Diffusion of Power Technology in British Industry. 1760-1870.*
[27] '*Population Of The Several Counties Of Great Britain - Hansard - UK Parliament*'; Wrigley, '*English County Populations in the Later Eighteenth Century*'.

models, are estimated to comprehensively identify significant interrelationships between regions and to detect the presence of spatial spillovers in a comprehensive way.

The results for the estimation of the spatial econometric models are in Table 2.

The parameter of spatial autocorrelation ρ is positive and significant across multiple specifications, reiterating the importance of imitative behaviour, since similar levels of adoption are found in neighbouring counties. The lagged variables show quite large positive local spillovers from the number of cotton mills and iron furnaces, supporting claims of other kind of agglomerative pattern influencing the diffusion of steam engines. The variable related to wool mills show negative influence on the diffusion of steam engines, but this is consistent with results from Nuvolari and co-authors and could be traced back to peculiarities of the integration of steam power in this industry. The negative effect of the lagged number of wool mills shows a tendency for isolated centres of production rather than agglomeration. The number of mines seems to be only directly influencing the diffusion, while spillovers appear to be irrelevant for this dimension. The magnitude of some effects changes with the different weighting matrix (for example, the lagged effect of the number of cotton mills and furnaces). In particular, the effects are larger with the *M* matrix, which considers larger neighbourhoods than *W*.

Table 2: estimation results according to W contiguity-based weighting matrix and M inverse-distance with 120 km cut-off weighting matrix.
source: own elaborations on multiple sources. See text for more information.

	Dependent variable: $log\ (SteamEngine + 1)$					
		W matrix			M matrix	
	(SAR)	(SDM)	(SLX)	(SAR)	(SDM)	(SLX)
Coal output	0.0002	0.001*	0.001	0.0003	0.001**	0.001**
	(0.0003)	(0.0004)	(0.0005)	(0.0004)	(0.0004)	(0.0004)
Waterwheels	0.002	0.002	0.002	0.002	-0.003	-0.003
	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Furnaces	0.079***	0.059**	0.073**	0.086***	0.056*	0.058*
	(0.029)	(0.028)	(0.033)	(0.031)	(0.029)	(0.032)
Cotton mills	0.018***	0.017***	0.020***	0.018***	0.014**	0.016**
	(0.005)	(0.006)	(0.007)	(0.006)	(0.006)	(0.006)
Wool mills	-0.003	-0.004	-0.006	-0.004	0.001	-0.0002
	(0.006)	(0.006)	(0.007)	(0.006)	(0.007)	(0.008)
Mines	0.045***	0.044***	0.045***	0.045***	0.029***	0.030***
	(0.007)	(0.007)	(0.008)	(0.007)	(0.008)	(0.009)
Population (log)	0.015	0.067**	0.063*	0.017	0.772***	0.741***
	(0.019)	(0.031)	(0.036)	(0.023)	(0.188)	(0.207)
Coal output (lag)		-0.002*	-0.002		-0.003**	-0.003*

		(0.001)	(0.001)		(0.001)	(0.001)
Waterwheels (lag)		0.001	0.002		0.008^{**}	0.009^{**}
		(0.002)	(0.002)		(0.003)	(0.004)
Furnaces (lag)		0.125^{**}	0.193^{***}		0.202^{**}	0.247^{**}
		(0.056)	(0.061)		(0.098)	(0.103)
Cotton mills (lag)		0.041^{**}	0.053^{**}		0.088^{***}	0.103^{***}
		(0.021)	(0.024)		(0.025)	(0.027)
Wool mills (lag)		-0.022	-0.025		-0.055^{**}	-0.063^{**}
		(0.014)	(0.017)		(0.026)	(0.029)
Mines (lag)		0.001	0.023		0.026	0.041
		(0.018)	(0.020)		(0.027)	(0.029)
Population (log, lag)		-0.070^{*}	-0.053		0.786^{***}	-0.745^{***}
		(0.037)	(0.043)		(0.196)	(0.215)
Observations	89	89	89	89	89	89
ρ	0.382^{***}	0.424^{***}		0.357^{***}	0.262	
Akaike Inf. Crit.	257.554	259.174	266.174	269.309	253.875	253.741
Note:						*p<0.1 ;**p<0.05 ;***p<0.01

The coefficients of the non-lagged variables of the SAR and SDM models are not directly interpretable as marginal effects, and should be split into direct and indirect (global) effects. I hereby show in Table 3 the effects of the two SDM models. Global effects (given by the spillovers and the feedback effects) are significant for several dimensions of the analysis. In particular, spillovers and feedback effects (i.e., indirect) appear to be larger than the direct effects for the variables representing the iron and cotton sectors.

Table 3: direct, indirect, and total effects for SDM models for both weighting matrices considered. source: own elaborations on multiple sources. See text for more information.

	W matrix			M matrix		
	Direct	Indirect	Total	Direct	Indirect	Total
Coal output	0,0005	-0,0024	-0,0019	$0,0008^{**}$	$-0,0031^{**}$	-0,0023
Waterwheels	0,0020	0,0033	$0,0053^{*}$	-0,0028	$0,0099^{**}$	0,0070
Furnaces	$0,0759^{***}$	$0,2444^{***}$	$0,3203^{***}$	$0,0688^{*}$	$0,2801^{**}$	$0,3489^{***}$
Cotton mills	$0,0226^{***}$	$0,0785^{**}$	$0,1011^{**}$	$0,0191^{***}$	$0,1191^{***}$	$0,1383^{***}$
Wool mills	-0,0069	-0,0385	-0,0454	-0,0019	$-0,0713^{*}$	$-0,0732^{*}$
Mines	$0,0462^{***}$	0,0327	$0,0789^{**}$	$0,0307^{***}$	0,0428	$0,0735^{*}$

Population (log)	0,0623**	-0,0680*	-0,0057	0,7368***	-0,7560***	-0,0192
Note:						*p<0.1 ;**p<0.05 ;***p<0.01

III – CONCLUSIONS

[To be added at later time]

References

Atack, J., F. Bateman, and T. Weiss. ‘The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing’. *The Journal of Economic History* 40 (1980), pp. 281–308.

Atack, J., R.A. Margo, and P. Rhode. ‘“Mechanization Takes Command”: Inanimate Power and Labor Productivity in Late Nineteenth Century American Manufacturing’. Working Paper, Working Paper Series, (2020). https://doi.org/10.3386/w27436.

Beckett, J.V. and J.E. Heath. ‘When Was The Industrial Revolution In The East Midlands?’ *Midland History* 13 (1988), pp. 77–94.

Brown, L.A. and K.R. Cox. ‘Empirical Regularities in the Diffusion of Innovations’. *Annals of the Association of American Geographers* 61 (1971), pp. 551–59.

Chapelain, C.L. and R.A. Wilke. ‘Steam Technology Diffusion in the 19th Century - First Evidence from Spatial Panel Data’, n.d.

Chapman, S.D. ‘Fixed Capital Formation in the British Cotton Industry, 1770–1815’. *The Economic History Review* 23 (1970), pp. 235–53.

Comin, D., M. Dmitriev, and E. Rossi-Hansberg. ‘The Spatial Diffusion of Technology’, (Cambridge, MA, November 2012). https://doi.org/10.3386/w18534.

Cox, G.W. and V. Figueroa. ‘Agglomeration and Creativity in Early Modern Britain’. *Explorations in Economic History* 95 (2025), p. 101644.

Diebolt, C., C.L. Chapelain, and A.-R. Menard. ‘Industrialization as a Deskilling Process? Steam Engines and Human Capital in XIXth Century France’, 2017.

Diebolt, C., C. Le Chapelain, and A.-R. Menard. ‘Learning Outside the Factory: A Cliometric Reappraisal on the Impact of Technological Change on Human Capital Accumulation’. *The European Journal of the History of Economic Thought* 26 (2019), pp. 775–800.

Flinn. *The History of the British Coal Industry*, (1984). http://archive.org/details/historyofbritish0000unse_n7l6.

Graevenitz, G. von, S.J.H. Graham, and A.F. Myers. ‘Distance (Still) Hampers Diffusion of Innovations’. *Regional Studies* 56 (2022), pp. 227–41.

Gutberlet, T. ‘Mechanization and the Spatial Distribution of Industries in the German Empire, 1875 to 1907’. *The Economic History Review* 67 (2014), pp. 463–91.

Hudson, P. ‘Regions and Industries: A Perspective on the Industrial Revolution in Britain’, 1989.

———. *The Industrial Revolution*, (1992).

Kanefsky, J.W. *The Diffusion of Power Technology in British Industry. 1760-1870.*, (Ph.D., University of Exeter, 1979).

Kanefsky, J. and J. Robey. ‘Steam Engines in 18th-Century Britain: A Quantitative Assessment’. *Technology and Culture* 21 (1980), p. 161.

Kaur, P., G. Punia Nakai, and N. Kaur. ‘Spatial Spillover of Product Innovation in the Manufacturing Sector: Evidence from India’. *Journal of the Knowledge Economy* 13 (2022), pp. 447–73.

Koo, J. ‘Determinants of Localized Technology Spillovers: Role of Regional and Industrial Attributes’. *Regional Studies* 41 (2007), pp. 995–1011.

Nuvolari, A., B. Verspagen, and N. von Tunzelmann. ‘The Early Diffusion of the Steam Engine in Britain, 1700–1800: A Reappraisal’. *Cliometrica* 5 (2011), pp. 291–321.

Nuvolari, A., B. Verspagen, and N. Von Tunzelmann. ‘The Early Diffusion of the Steam Engine in Britain, 1700–1800: A Reappraisal’. *Cliometrica* 5 (2011), pp. 291–321.

Pollard, S. ‘Industrialization and the European Economy’. *The Economic History Review* 26 (1973), pp. 636–48.

———. *Peaceful Conquest : The Industrialization of Europe, 1760-1970*, (1981). http://archive.org/details/peacefulconquest0000poll.

‘Population Of The Several Counties Of Great Britain - Hansard - UK Parliament’. https://hansard.parliament.uk/. Accessed 25 August 2023. https://hansard.parliament.uk/Commons/1812-01-18/debates/c18a69f4-c97e-43a1-a533-b53f592bf27a/PopulationOfTheSeveralCountiesOfGreatBritain.

Scrivenor, H. *History of the Iron Trade*, (1967). http://archive.org/details/historyofirontra0000harr.

Tobler, W.R. ‘A Computer Movie Simulating Urban Growth in the Detroit Region’. *Economic Geography* 46 (1970), pp. 234–40.

Von Tunzelmann, G.N. *Steam Power and British Industrialization to 1860*, (1978). http://archive.org/details/steampowerbritis0000vont.

Wrigley, E.A. ‘English County Populations in the Later Eighteenth Century’. *The Economic History Review* 60 (2007), pp. 35–69.